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The traditional "evaporation/melt and blow" mechanism of CO_2 laser cutting of aluminum nitride (AlN) chip carriers and heat sinks suffers from energy losses due to its high thermal conductivity, formation of dross, decomposition to aluminum, and uncontrolled thermal cracking. In order to overcome these limitations, a thermochemical method that uses a defocused laser beam to melt a thin layer of AlN surface in oxygen environment was utilized. Subsequent solidification of the melt layer generated shrinkage and thermal gradient stresses that, in turn, created a crack along the middle path of laser beam and caused material separation through unstable crack propagation. The benefits associated with thermal stress fracture method over the traditional method are improved cut quality, higher cutting speed, and lower energy losses. [DOI: 10.1115/1.2912223]

Keywords: aluminum nitride, cutting, laser, thermal stress, packaging material

Aluminum nitride (AlN) is an effective electronic packaging material due to its excellent dielectric constant (8.6), high volume resistivity (10^{10} Ω cm), and extraordinary thermal conductivity (150 W/m K). In addition, the superior high-temperature and chemical resistance properties made it also a useful choice for molten metal crucibles and heat exchangers. Diamond sawing and scribing/breaking are currently used to perform "singulation" of AlN for heat sinks and other electronic packaging applications [1]. The major concerns with diamond machining are short and unpredictable blade lifetimes, poor positioning accuracy, and uncontrolled crack formation. In addition, AlN also fails during the diamond cutting process due to the formation of superficial and internal cracks and presence of nonuniform voids. A flexible tool such as laser beam that is unaffected by the high hardness of AlN has potential to overcome the problems associated with diamond machining.

CO_2 laser machining (scribing, drilling, and cutting) of monolithic ceramics such as aluminum oxide and aluminum nitride is gaining rapid industrial acceptance as an alternative to diamond machining methods due to benefits such as higher speed and lower cost [2–4]. However, the mechanism of material removal is a combination of evaporation and melt/blow that, in turn, requires extreme power lasers, leads to unwanted liquid and gaseous phases (recast layer, burr formation, and chemical decomposition), and causes thermal stresses that result in uncontrolled fracture. The process does not also allow successful cutting of thicker sections (>2 mm). These problems seem to be particularly more acute in AlN due to its high thermal conductivity and relatively poor chemical stability. For example, Coherent, Inc. utilized a 500 W sealed CO_2 laser to drill, scribe, and cut AlN [2]. The central issues noted in this study were very low cutting speed and decomposition of AlN to form aluminum metal. Oxygen assist gas was used to improve the speed while preventing the formation of metallic aluminum. There are a number of laser job shops in the U.S. that perform laser machining services of monolithic ceramics including AlN. However, premature fractures and low cutting speeds are still the greatest obstacles, particularly when thick sections are involved. A premachining treatment such as the application of polyvinyl alcohol (PVA) coating was used to minimize contamination and reduce slag buildup around holes and scribe areas. In addition, a postannealing treatment is necessary to relieve the stresses introduced during the laser machining process.

The increased requirements of flexibility and precision in design and manufacturing of AlN necessitate development of new laser techniques. In this work, we report an improved laser cutting process for AlN that relies upon principle of thermal stresses to initiate the controlled crack followed by separation of material rather than by traditional melting and evaporation. Results are compared with conventional laser cutting on productivity, energy loss, and cut quality. Thermal stress technique consists of enlarging the laser beam's spot size (by defocusing the beam or using a large focal length lens) by five to ten times over the conventional method so that only a thin surface layer is melted and resolidified in oxygen-rich environment. The shrinkage associated with phase transformation (aluminum nitride to aluminum oxide) coupled with temperature gradients in a zone approximately equal to thermal diffusion depth drive the development of thermal stresses, which results in crack formation followed by material separation. Rapid cooling rather than rapid heating will inflict most of thermal shock since the induced surface stresses are tensile in nature during rapid cooling.

In this work, 1 mm thick aluminum nitride plates of size 115×115 mm^2, provided by *Ceramtec*, were cut using a 500 W CO_2 laser. AlN with a nominal composition of 97% AlN and 2% Y_2O_3 (sintering aid) was produced by hot pressing powder metallurgy techniques. It is stable at high temperatures only in inert environment. In air, however, surface oxidation occurs above 700°C, which forms a layer of aluminum oxide. It also dissociates above 2500°C at atmospheric pressure to aluminum metal. Samples of the nominal size 25×25 mm^2 were prepared by traditional laser cutting that was performed on a computer numerically controlled (CNC) worktable using a continuous wave, 10.6 μm wavelength CO_2 laser with a power capacity of 1500 W (Model 820 Spectra Physics). Following sample preparation, two types of experiments were carried out.

The first set of experiments was traditional (conventional) laser cutting using oxygen as the assist gas. The beam from the laser was sent through a circular polarizer and then directed into a focusing lens in a gas-jet cutting assembly. The 127 mm focal length lens produced a theoretical focal spot diameter of 0.2 mm at the sample surface. The laser power was varied from 200 W to 500 W. Oxygen with a pressure of 207 kPa (30 psi) was delivered through a coaxial nozzle with a diameter of 2 mm. The nozzle was maintained at a standoff distance of 1–2 mm from the surface of the substrate. The sample was placed on *x-y* positioning table controlled by a computer numerical CNC controller. The cutting speed ranged from 1.6 mm/s (4 in./min) to 21 mm/s (50 in./min). Following laser cutting, sample preparation was completed by deburring the slag and cleaning it with methanol. The second set of experiments consisted of defocusing the beam to a theoretical spot size of 0.6 mm diameter on the sample surface. The laser power was varied from 200 W to 500 W while the cutting speed was made in the range of 4.2 mm/s (10 in./min) to 254 mm/s (600 in./min). Oxygen

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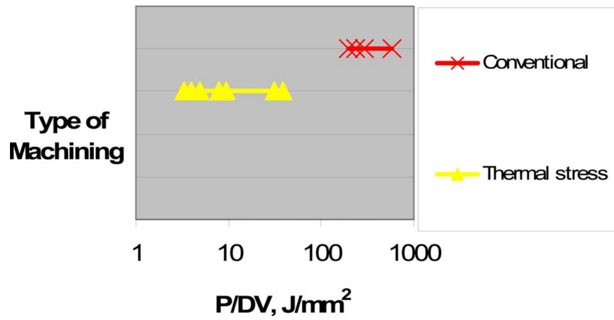

Fig. 1 Effect of energy density on type of cutting mechanism for 1 mm thick AlN

was again used as the assist gas. The cut quality was assessed by visual and scanning electron microscope examination of burr, fracture, cracks, and dross.

Figure 1 shows the effect of energy density parameter defined by P/DV (P is laser power, D is spot size, and V is cutting speed) on the material removal mechanism for 1 mm thick AlN. It can be seen that the conventional "evaporation/melt and blow" mode of material removal requires very high energy densities ($200-1000\ \mathrm{J/mm^2}$) and, in this range, the cut quality was found to increase with increasing P/DV. Coherent, Inc. used a 500 W power CO_2 laser to "conventional" cut 0.7 mm thick AlN with a focus spot of 100 μm at a speed of 2 mm/s, giving rise to an energy density of $P/DV=2500\ \mathrm{J/mm^2}$ [2], which is substantially higher than reported here. In contrast, thermal stress mode of material could be performed at energy densities that are almost two orders of magnitude lower than conventional mode. The differences are primarily attributed to the energy loss by heat conduction and phase transformation. Another observation is that the cutting speed for thermal stress fracture mode is an order of magnitude greater than conventional cut, which implies the potential industrial benefit of achieving higher productivity.

Conventional laser cutting is the standard practice in industry. Although fine kerfs of <0.2 mm were obtained in this mode, the key problems are significant amount of dross formation, decomposition of material, and poor surface integrity in terms of cracks and contamination. Figure 2 shows the longitudinal and transverse views of a typical conventional cut, which illustrates the dross, cracks, and debris in the heat affected zone. The dross tends to close off the kerf in many locations. Transverse section also exhibits striations as well as burrs/cracks at the bottom. Compositional analysis revealed the presence of aluminum oxide as the major species in the dross (recast layer). In a previous work on the conventional laser cut of AlN [2], the effect of different assist gases was examined. The samples cut with argon or nitrogen had conductive aluminum firmly attached to the cut edges. Argon-

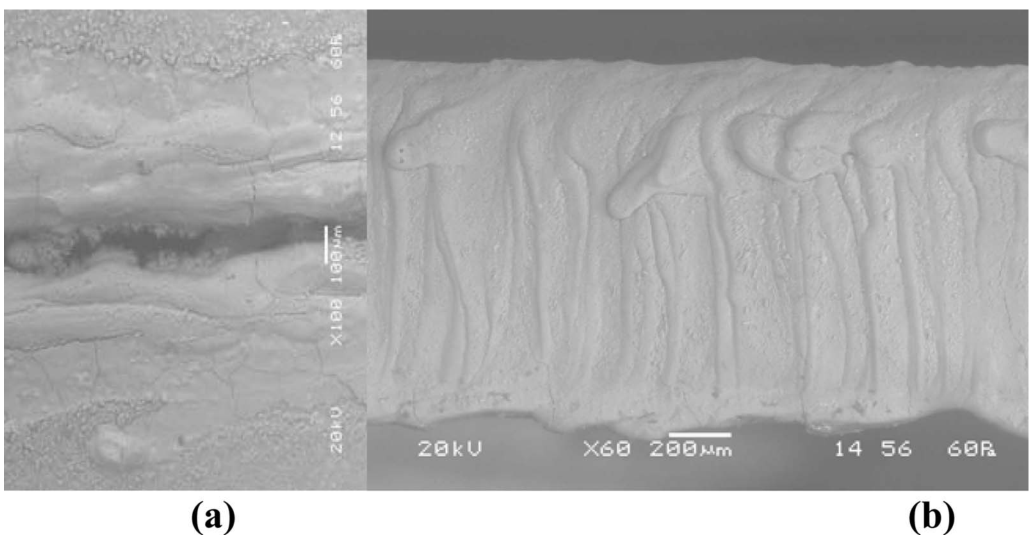

Fig. 2 (*a*) Top and (*b*) transverse sectional views of conventional laser-cut AlN ($P/DV=197\ \mathrm{J/mm^2}$)

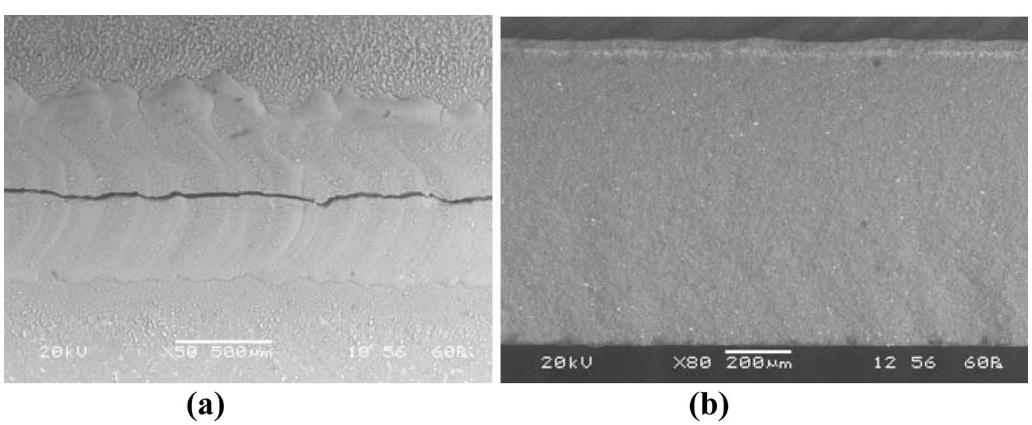

Fig. 3 (*a*) Top and (*b*) transverse sectional views of thermal stress fracture mode laser-cut AlN ($P/DV=39\ \mathrm{J/mm^2}$)

assisted samples also had a significant tendency to crack. The only good (nonconductive) edges were achieved with oxidizing-assist gas, with oxygen producing better visual edge quality than air.

Figure 3 shows the longitudinal and transverse views of the thermal stress fracture mode-cut sample at low energy density. In the longitudinal section, there is a thin melt layer and a fine crack in the middle, the width (20 μm in Fig. 3) of which became the kerf width. In the transverse section, a top layer of about 25 μm, composed of aluminum oxide, is seen. Higher magnification revealed a columnar solidification structure of this layer. The remaining section exhibited a "virgin" surface, a characteristic of fast fracture. There are no cracks or dross clinging on to the bottom surface, suggesting a "clean cut" process.

Thermal shock fracture, the stress caused by nonuniform thermal expansions/contractions, is a potential method [5] of material removal in ceramic materials. We have successfully applied this technique for aluminum nitride, a key material in electronic packaging with expanding sales over competing materials due to its ability to dissipate the greater heat load. The work showed that high quality cuts and high speeds can be achieved in thermal stress fracture mode over conventional laser cutting that, in turn, will meet the design requirements of high precision and productivity. It is believed that by increasing the quality and reliability of the finished products, the designer and end-user's reluctance to use AlN will be overcome.

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